SAS for LIGO 2

The LIGO 2

Seismic Attenuation System

Status Report

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

- LIGO –

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	DCC Number	Date
Presentation	**LIGO- G000128-00-R**	4th of May 2000

PAC8 Meeting

Caltech - May 1-2, 2000

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Seismic Attenuation System

Status Report

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Distribution of this draft: TBD
This is an internal working note
of the LIGO Project.

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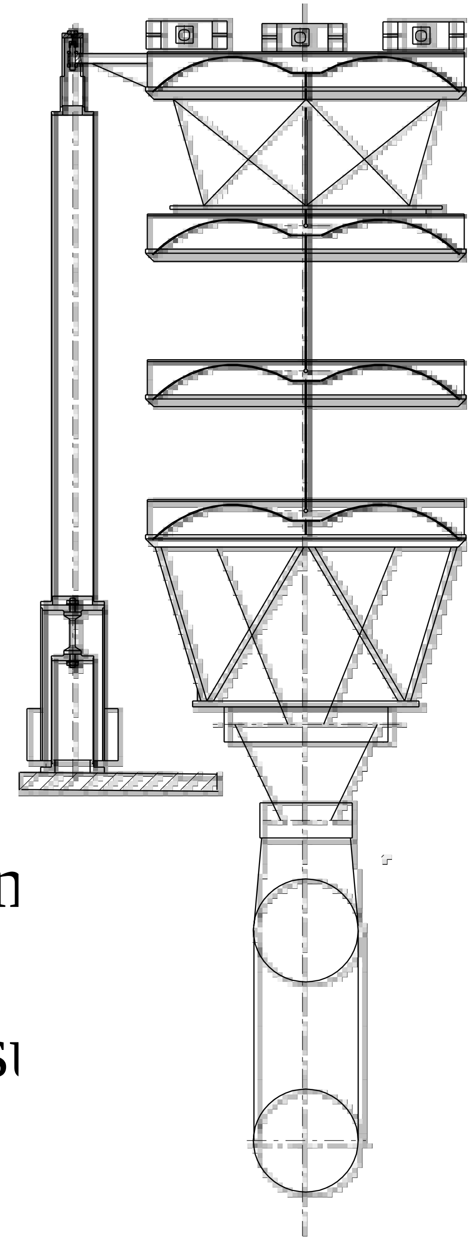
LIGO SAS

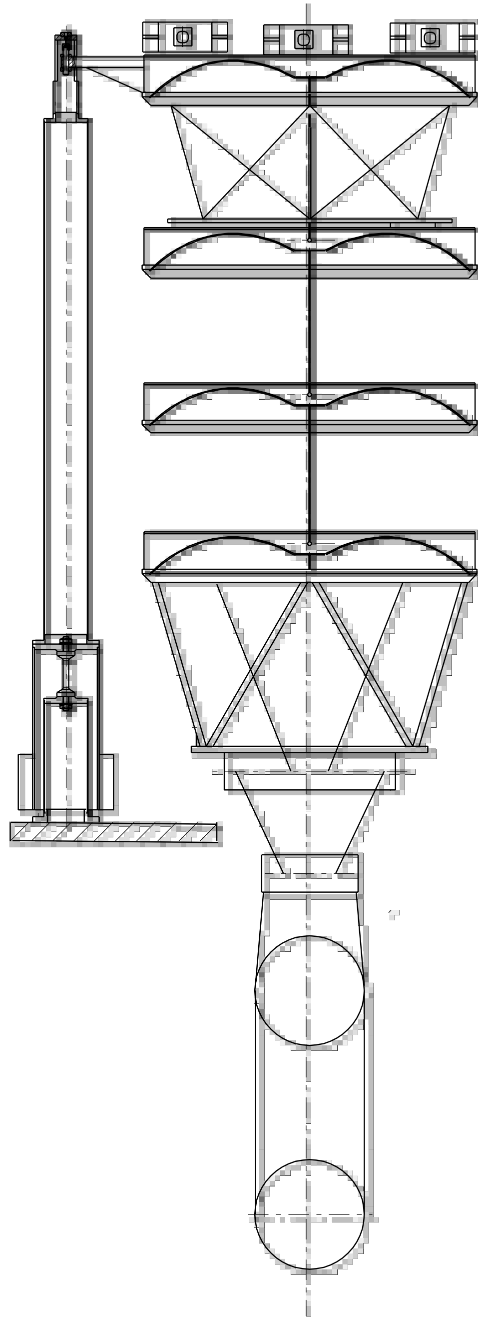
What is SAS

- Seismic Attenuation System
- Passive seismic attenuation chain
  - Preceded by a passive pre-isolator
  - Complemented with inertial dampin
  - Followed by a multiple pendulum su



LIGO SAS

A typical SAS chain



GASF Filter 0

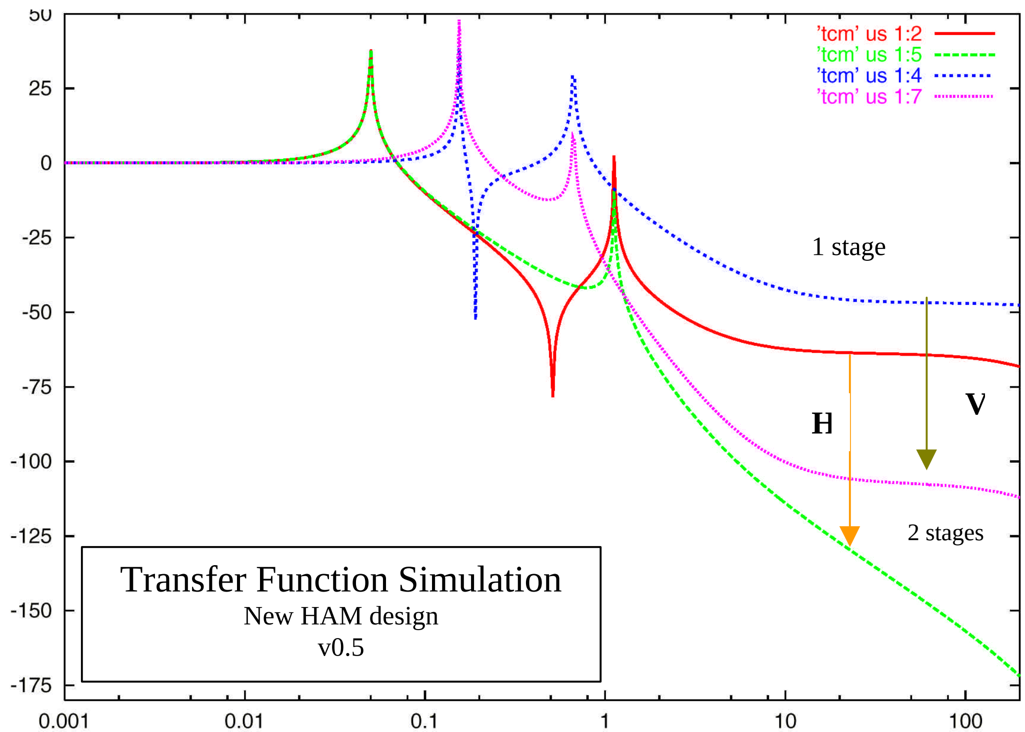
GASF Filters

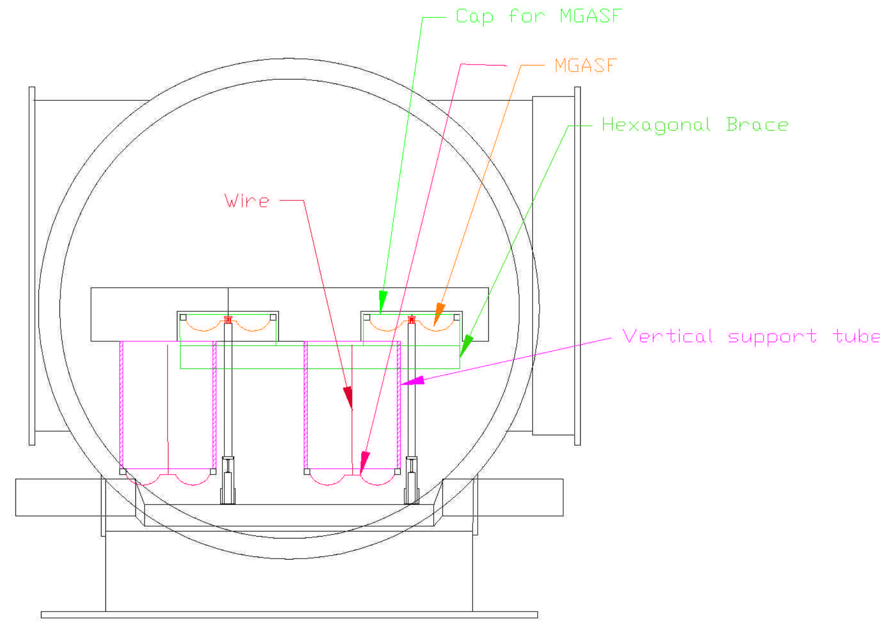
Inverted Pendulum

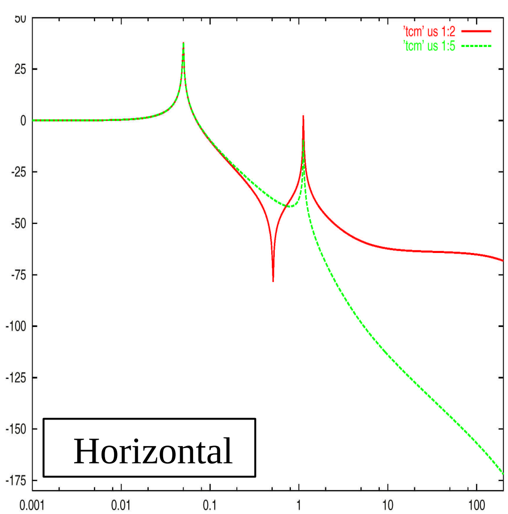
Only one leg shown

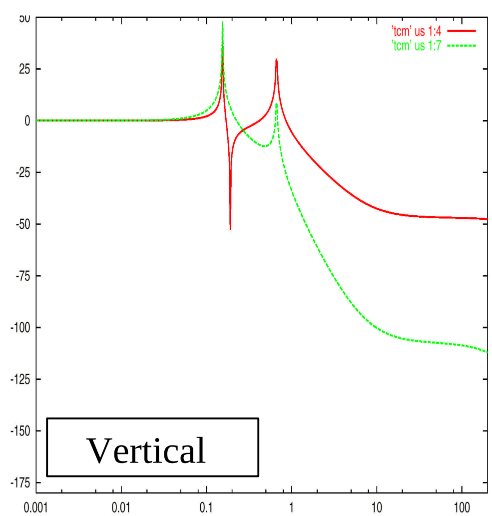
For simplicity

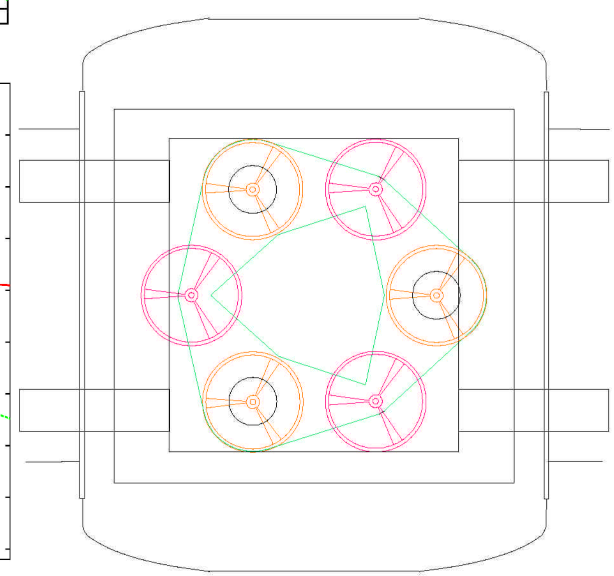
Multiple Pendulum Suspension


'tcm' us 1:2
'tcm' us 1:5
'tcm' us 1:4
'tcm' us 1:7
1 stage
H
V
2 stages
Transfer Function Simulation
New HAM design
v0.5
0.001
0.01
0.1
1
10
100


Cap for MGASF
MGASF
Hexagonal Brace
Wire
Vertical support tube


'tcm' us 1:2
'tcm' us 1:5
Horizontal


'tcm' us 1:4
'tcm' us 1:7
Vertical



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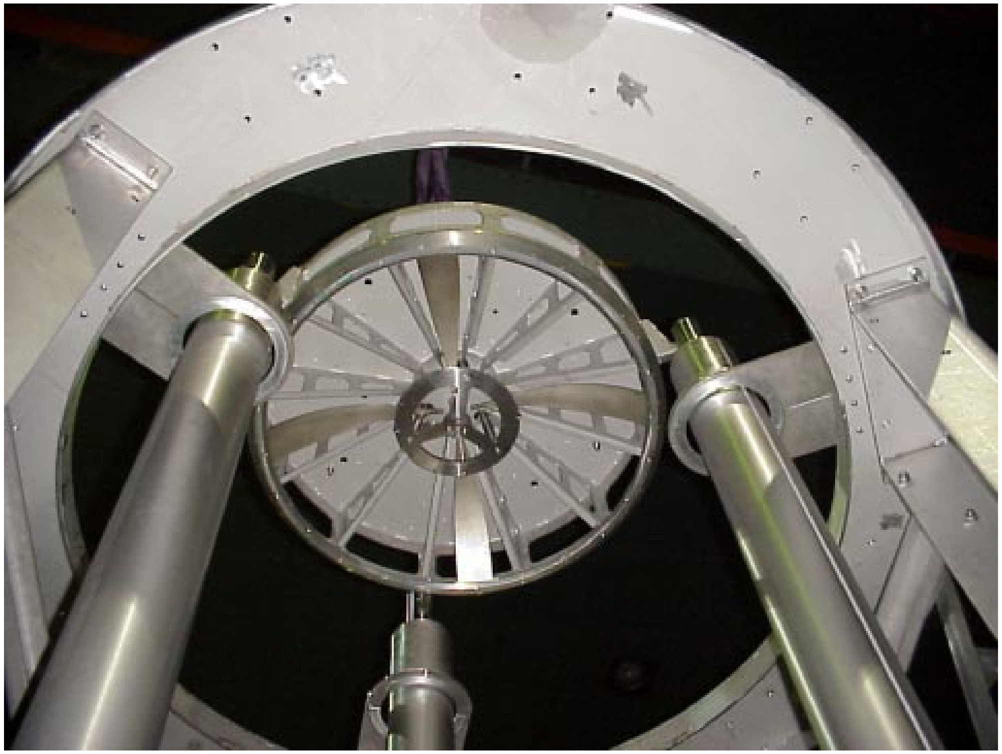
SAS Test Tower Prototype

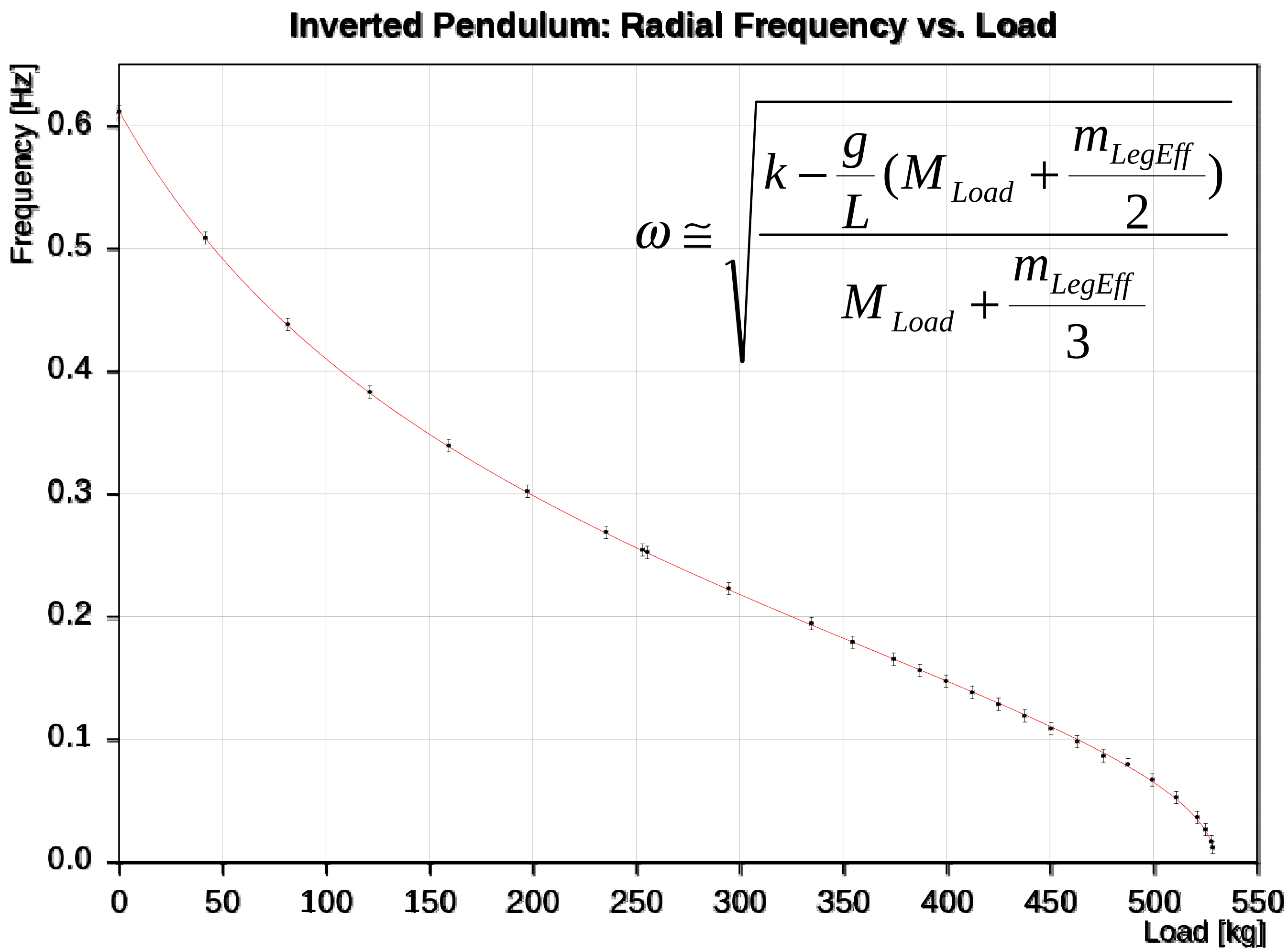


LIGO SAS

Pre-Isolator

- Pre-isolator: tuned at Ultra Low Frequencies
- To minimize seismic excitation of normal modes of the passive attenuation chain
- To allow sub-micron positioning of multiple pendulum Suspension point
- To provide an optimized mechanical base for Inertial Active Damping of ALL Attenuation Chain Resonant Modes
  - (**Inertial Damping** is **outside** the frequency region of interest, it is **not Active Attenuation ! ! !**)
- APS April 2000, Long Beach, Szabolcs Marka, ”Characterization of LIGO II/SAS Inverted Pendulum as Low Frequency Pre-Isolation”

LIGO SAS



$$\omega \cong \sqrt{\frac{k - \frac{g}{L}\left(M_{Load} + \frac{m_{LegEff}}{2}\right)}{M_{Load} + \frac{m_{LegEff}}{3}}}$$

APS April 2000, Long Beach, Szabolcs Marka, "Characterization of LIGO II/SAS Inverted Pendulum as Low Frequency Pre-Isolation"

Pre-Isolator advantages

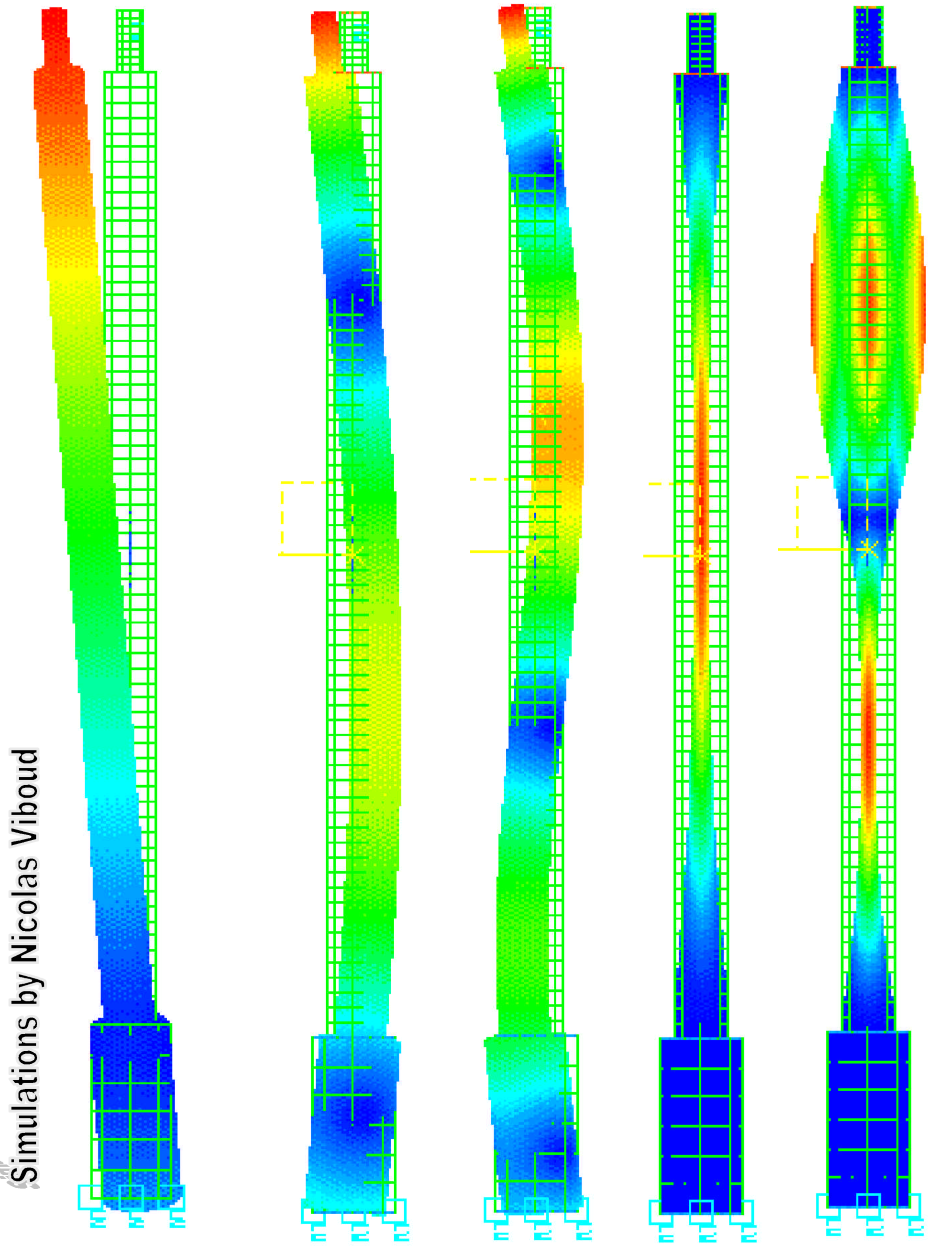
- IP naturally divides 3 + 1 degrees of freedom
  - Makes MIMO controls easy!
  - Much simpler than 6 d.o.f. feedback loops.

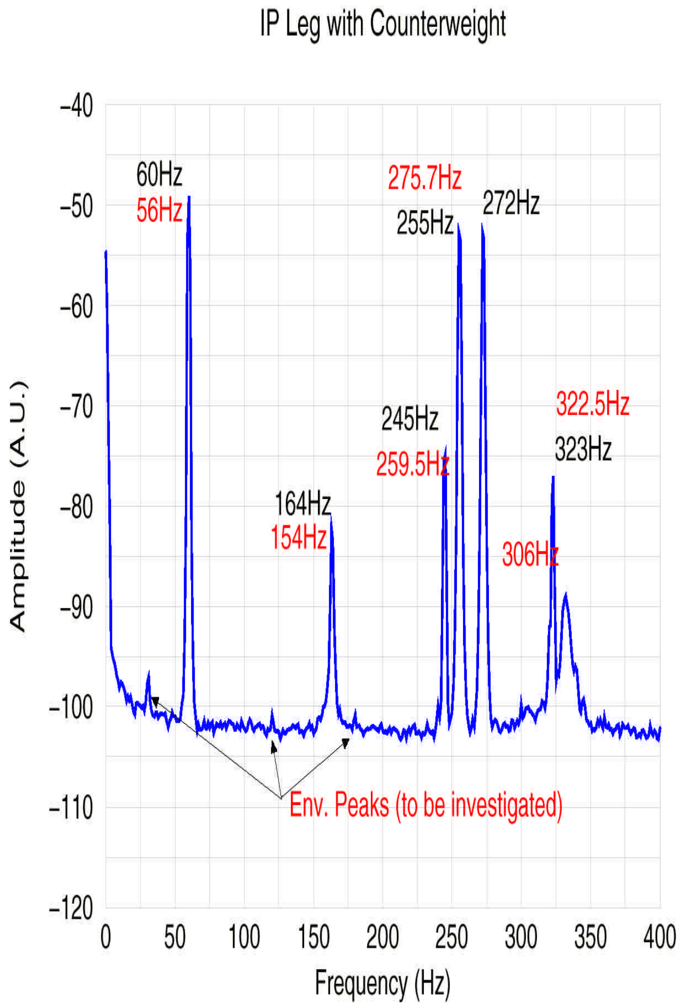
- IP is soft, 4 mN to move 1 ton by 1 mm at 10 mHz
      - » Figure Diagonalization of sensors.

Pre-Isolator performance

- In the micro-seismic peak frequency range
  - Attenuation >100
- In the passive chain resonance frequency band
  - Attenuation >1000

IP Leg + C.W Resonances





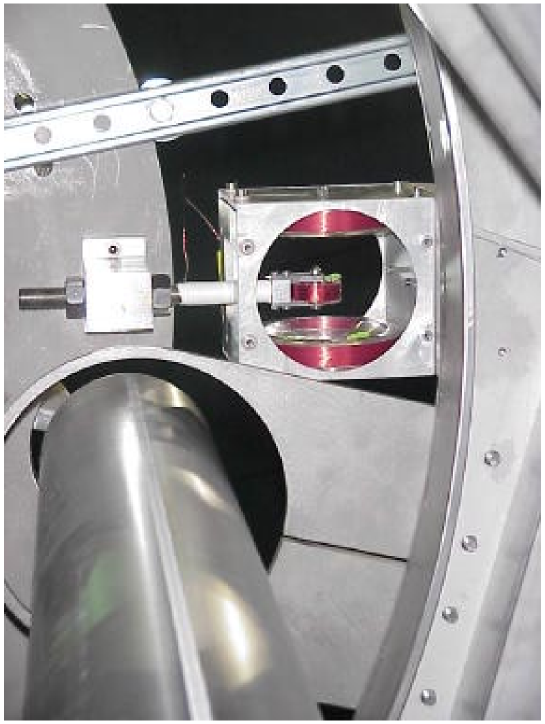
www.ligo.caltech.edu/~citsas

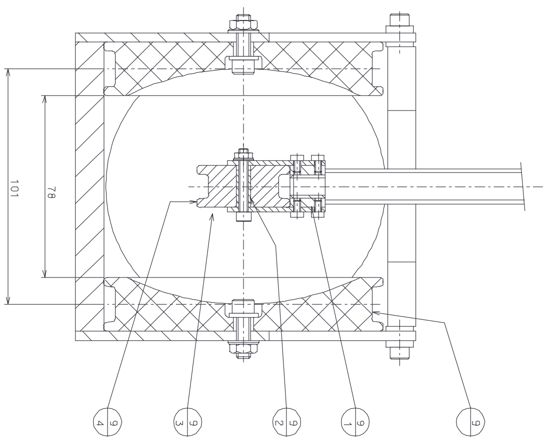
www.ligo.caltech.edu/~smarka

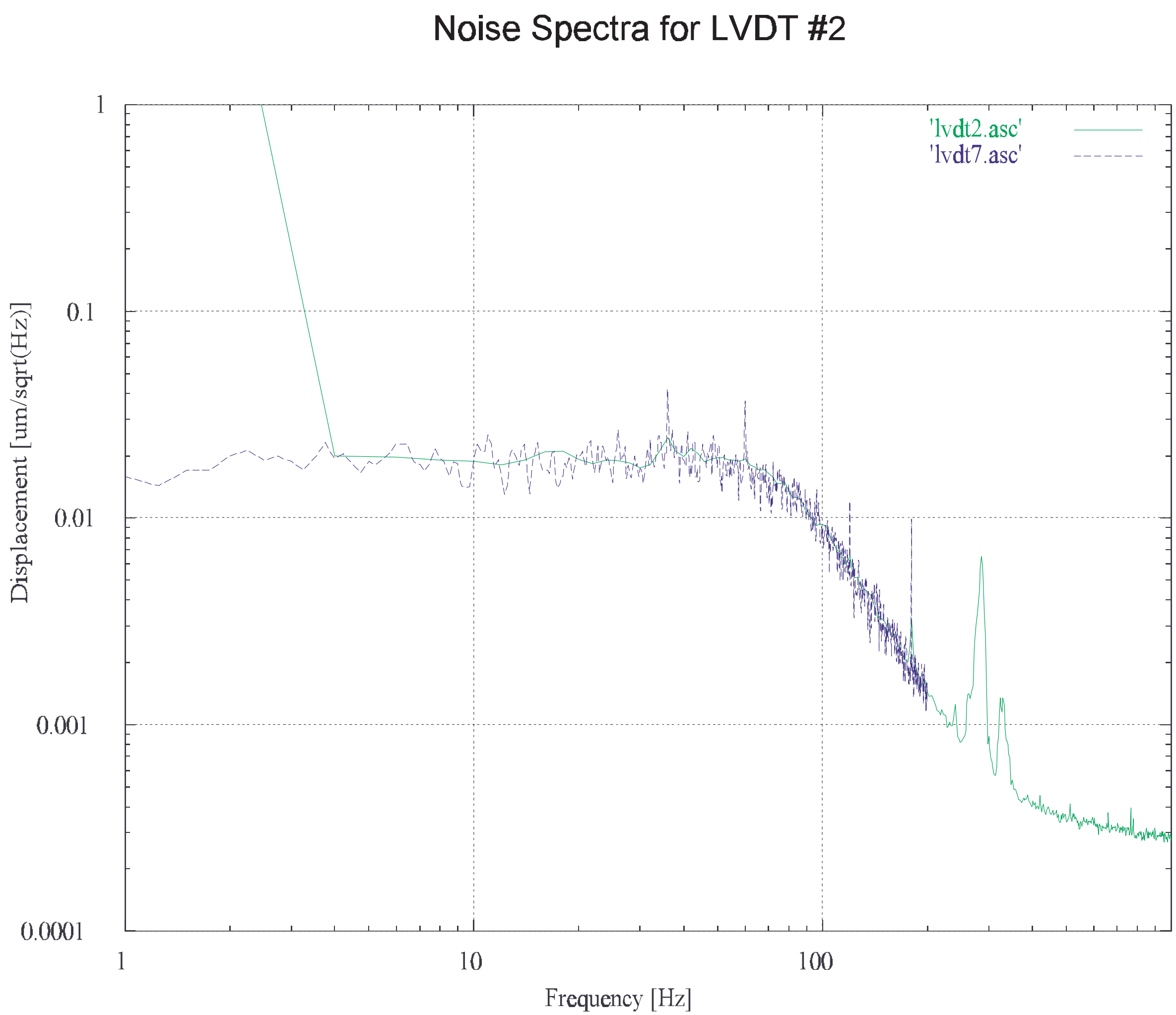
Positioning on Pre-Isolator

- Precision Positioning of Multiple Pendulum
  - Need good Passive Chain Modal Damping
  - APS April 2000, Long Beach, Virginio Sannibale, "Controls of Seismic Attenuation System (SAS) for the LIGO II Gravitational Wave Detector"
  - Need good well defined movements and soft mechanics
  - Need good position sensors
  - Need good zero force gradient actuators
  - Need good MIMO software

LIGO SAS







Hareem Tariq
Chenyang Wang

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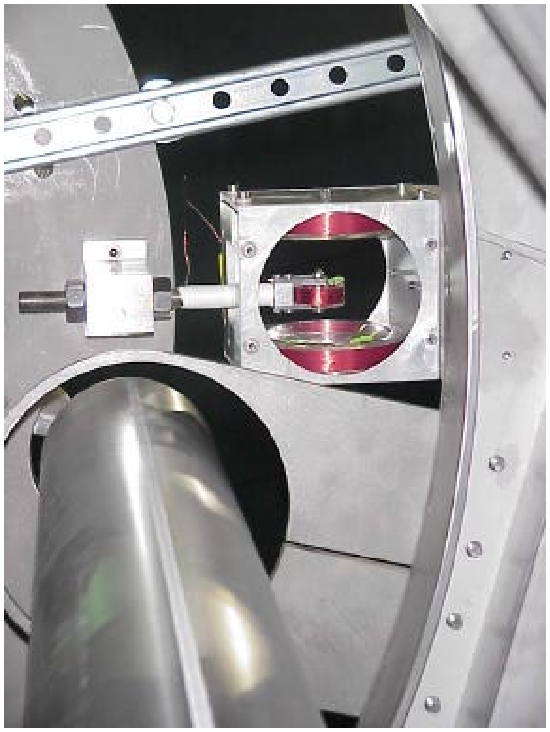

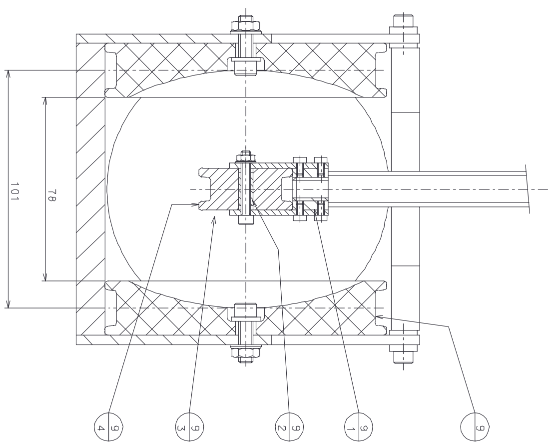

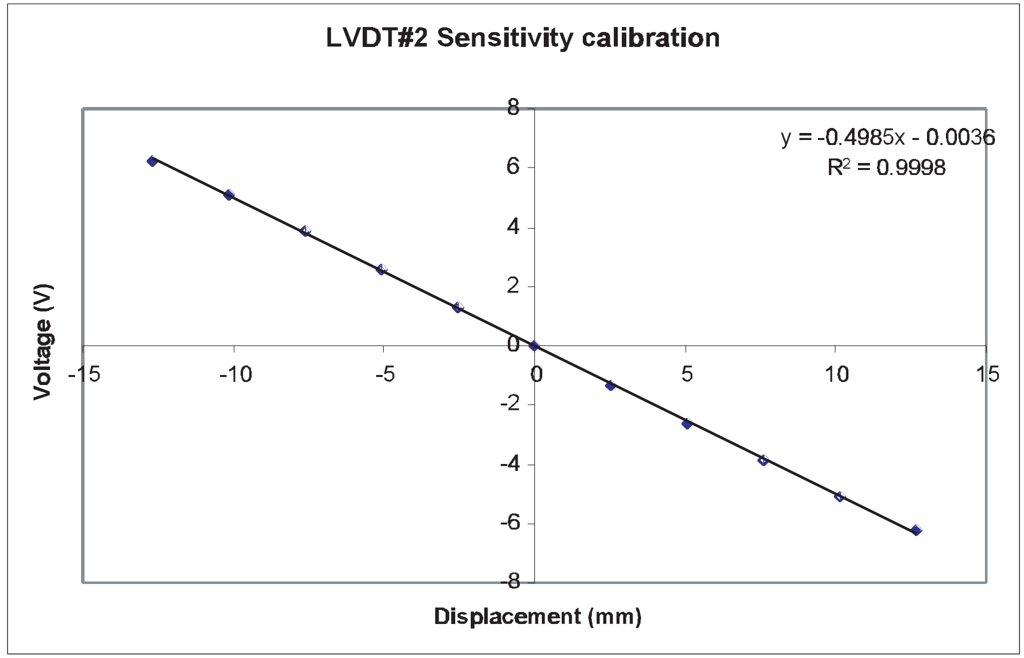

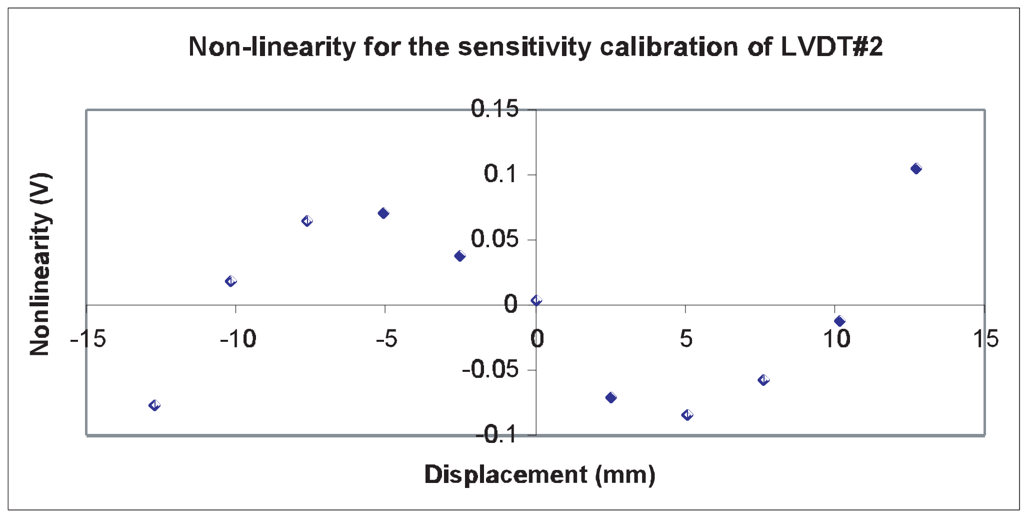

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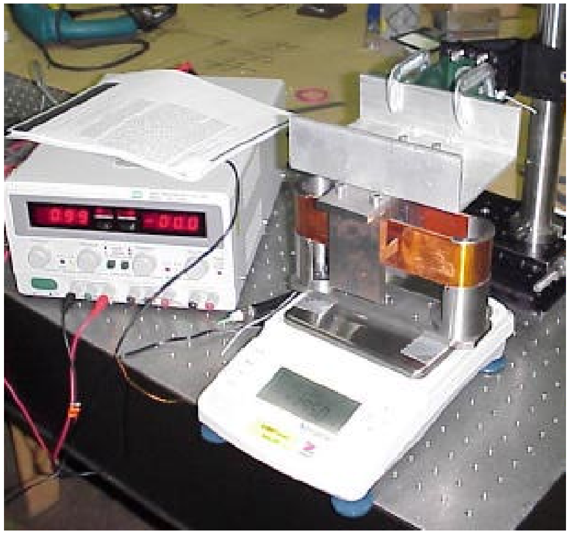
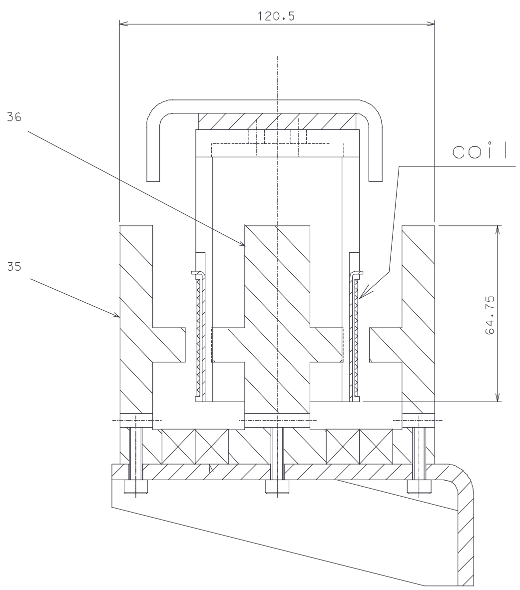
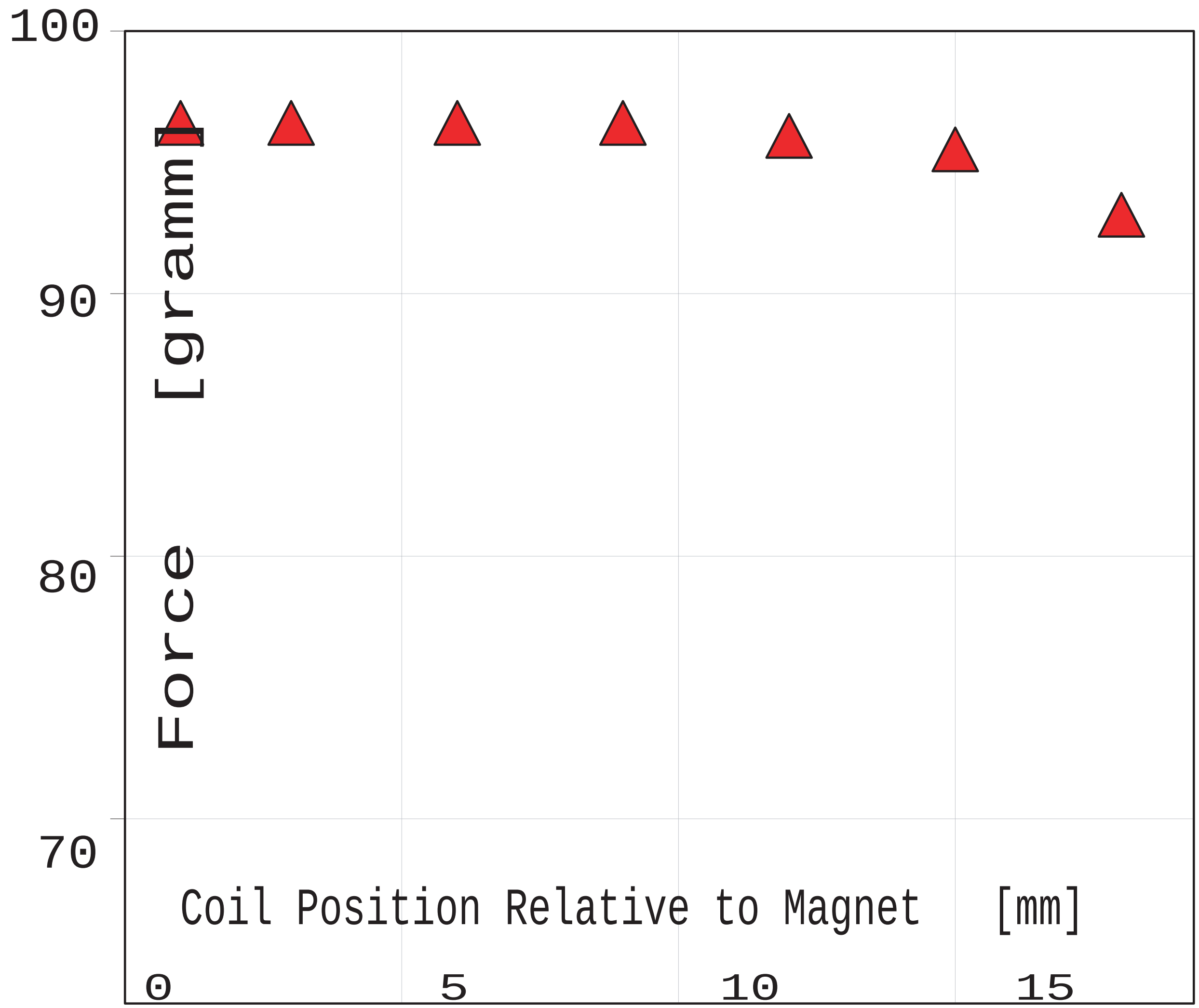
Force vs. Coil Position (Actuator

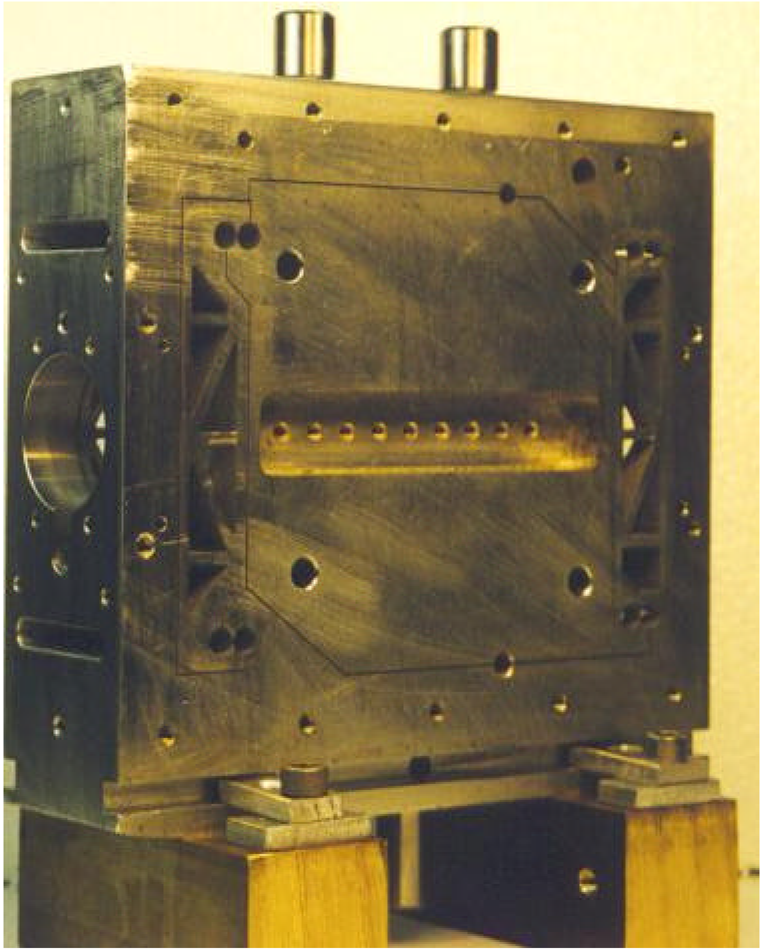


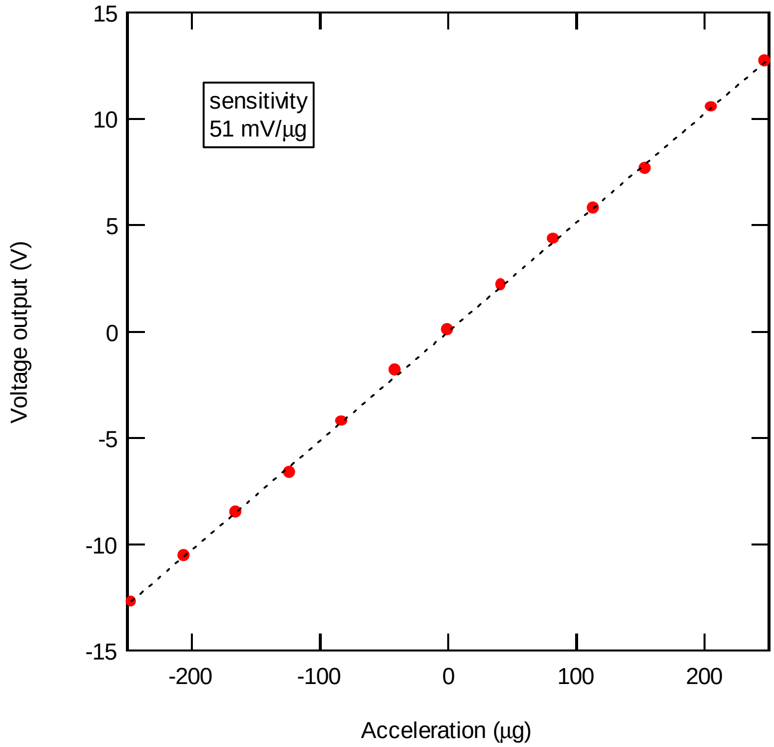




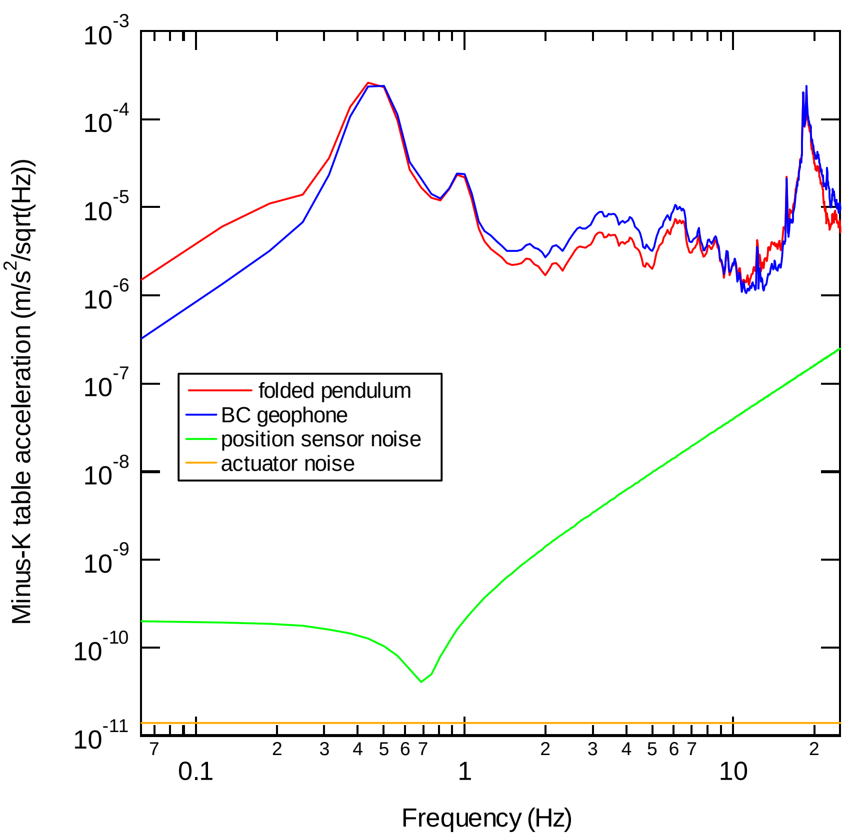
Inertial Modal Damping in Pre-Isolator

- A Good Damping of the Passive Chain internal modes
  - Needs well defined movements and soft mechanics
  - Needs good accelerometers
    - High sensitivity, insensitive to orthogonal accelerations
- APS April 2000, Long Beach, Alessandro Bertolini, “A very low noise monolithic Horizontal accelerometer”
  - Needs good zero force-gradient actuators
  - Needs good MIMO software





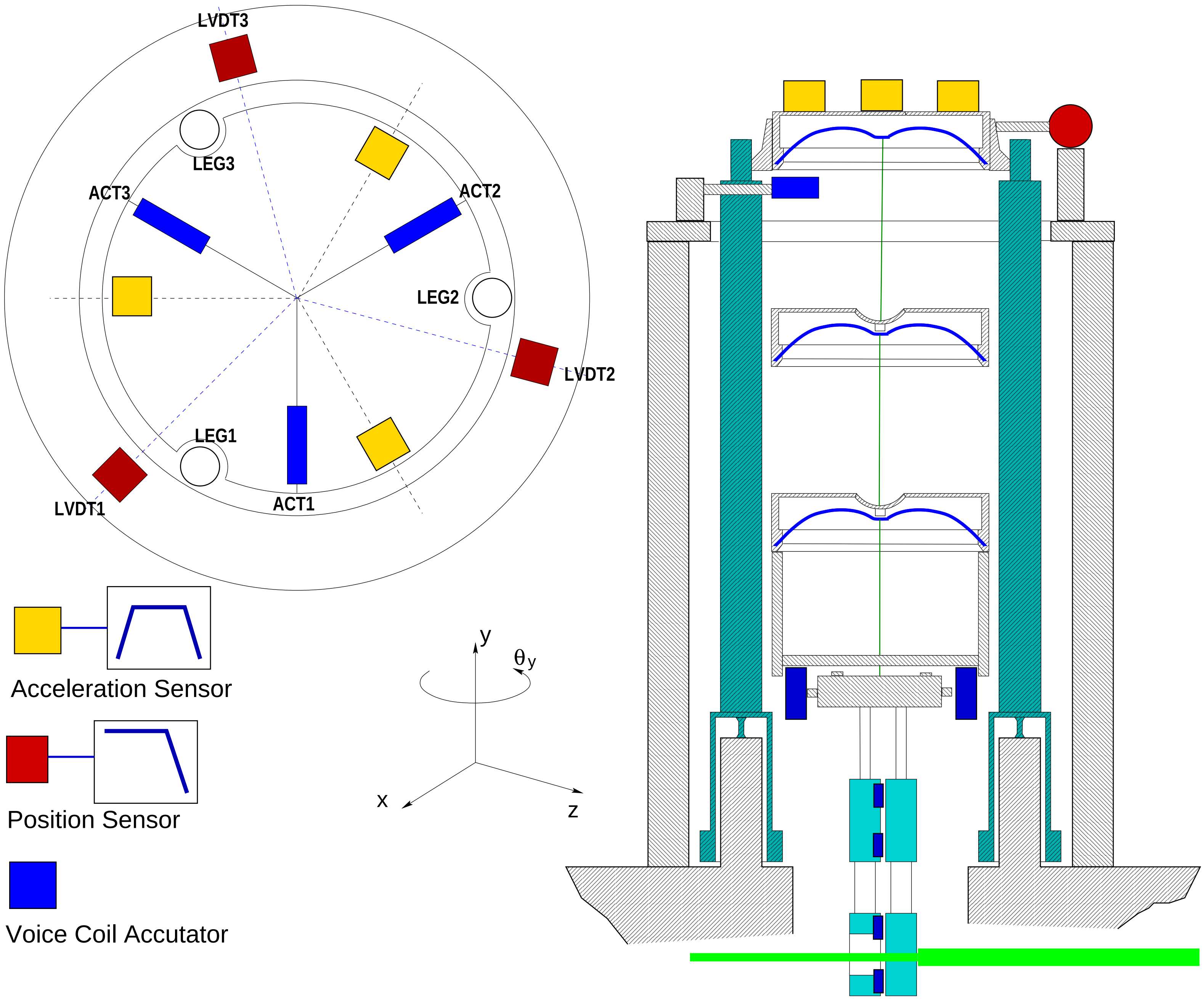
sensitivity
51 mV/µg
Voltage output (V)
Acceleration (µg)
15
10
5
0
-5
-10
-15
-200
-100
0
100
200



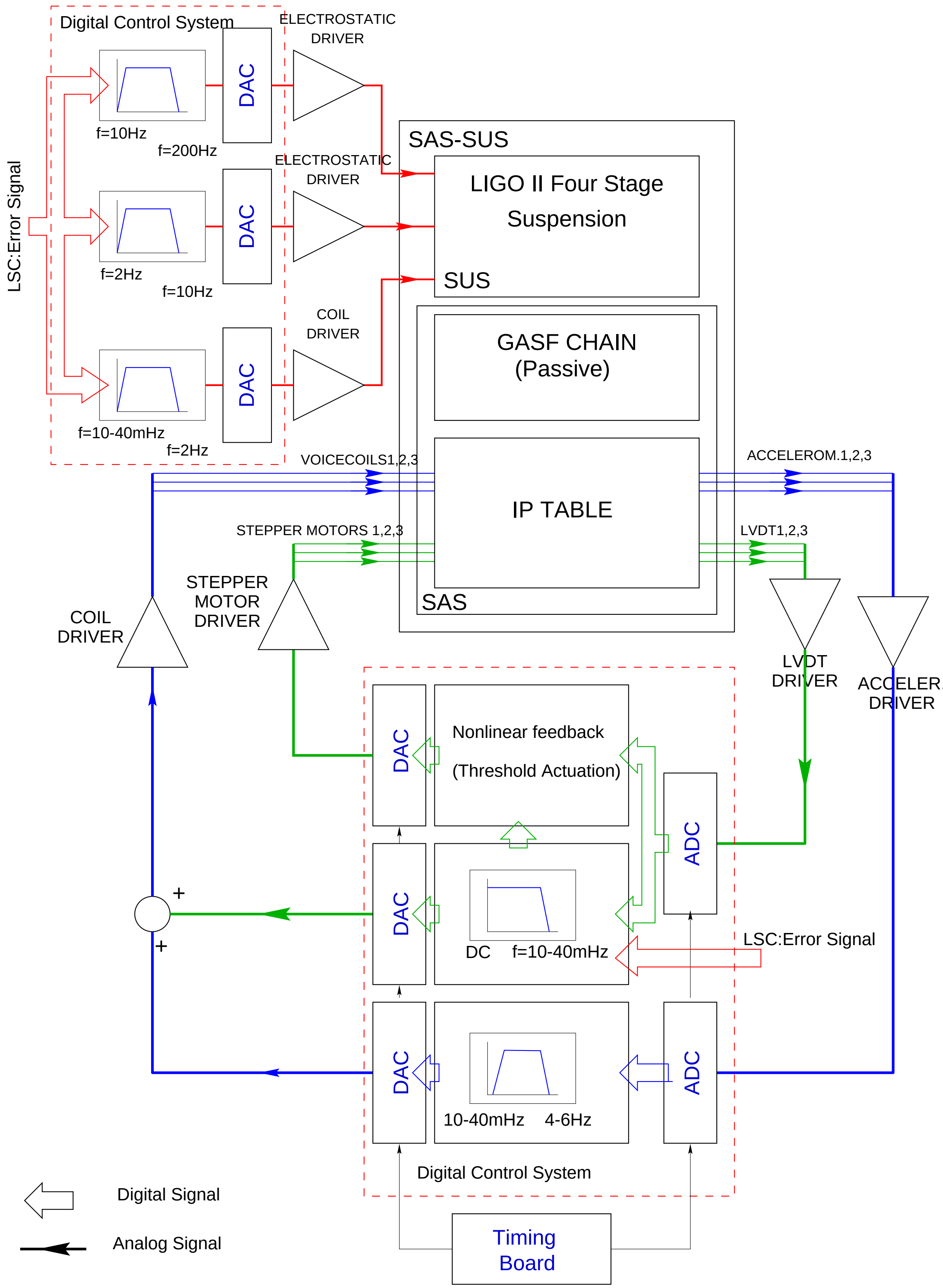
folded pendulum
BC geophone
position sensor noise
actuator noise
Minus-K table acceleration (m/s^2/sqrt(Hz))
Frequency (Hz)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10

SAS IP Sensor Actuator Map

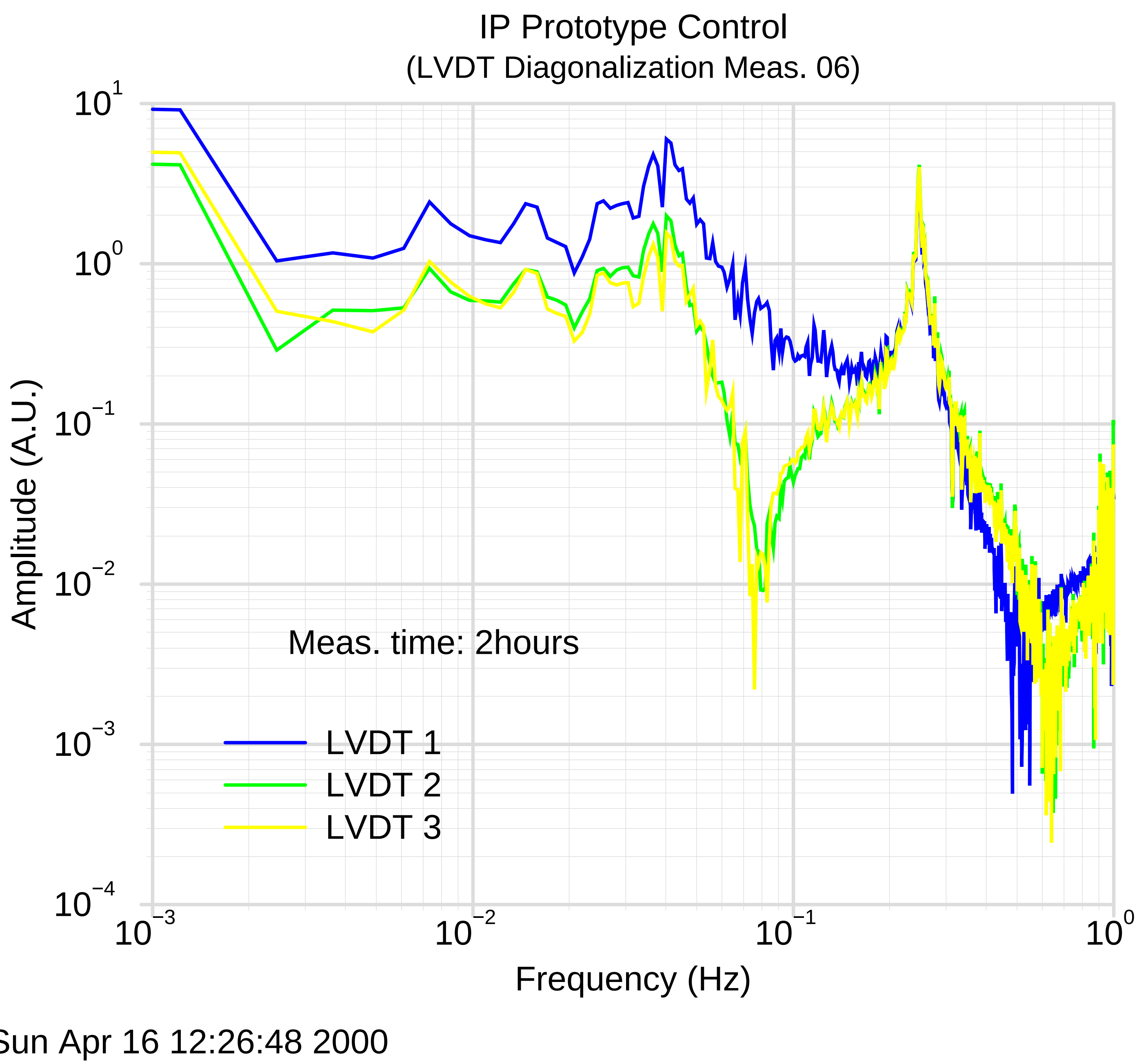
$(X, Y$ and $\theta_y)$



SAS-SUS Longitudinal Control Diagram

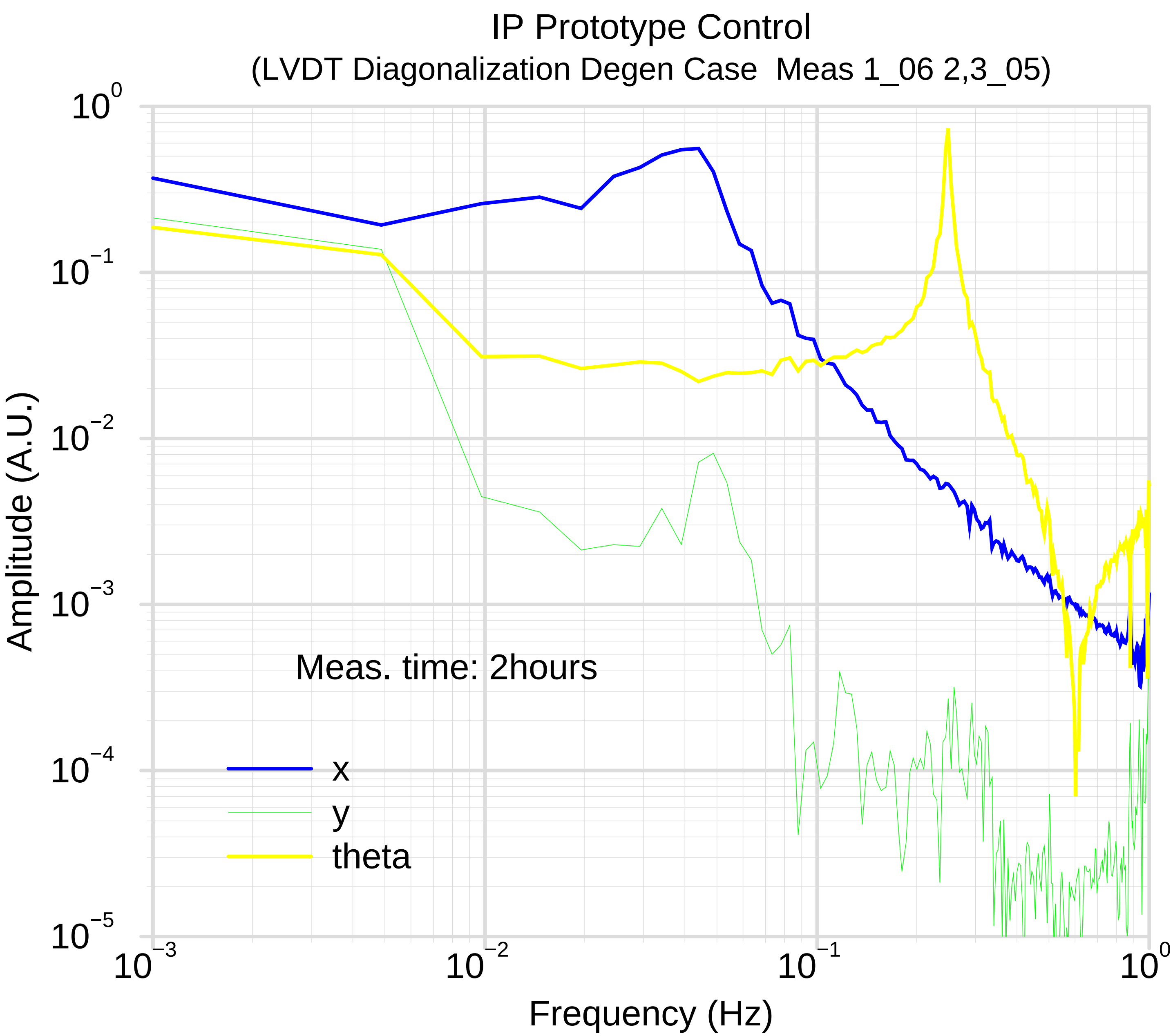


LVDT Sensors Diagonalization (Direct Transfer Functions)

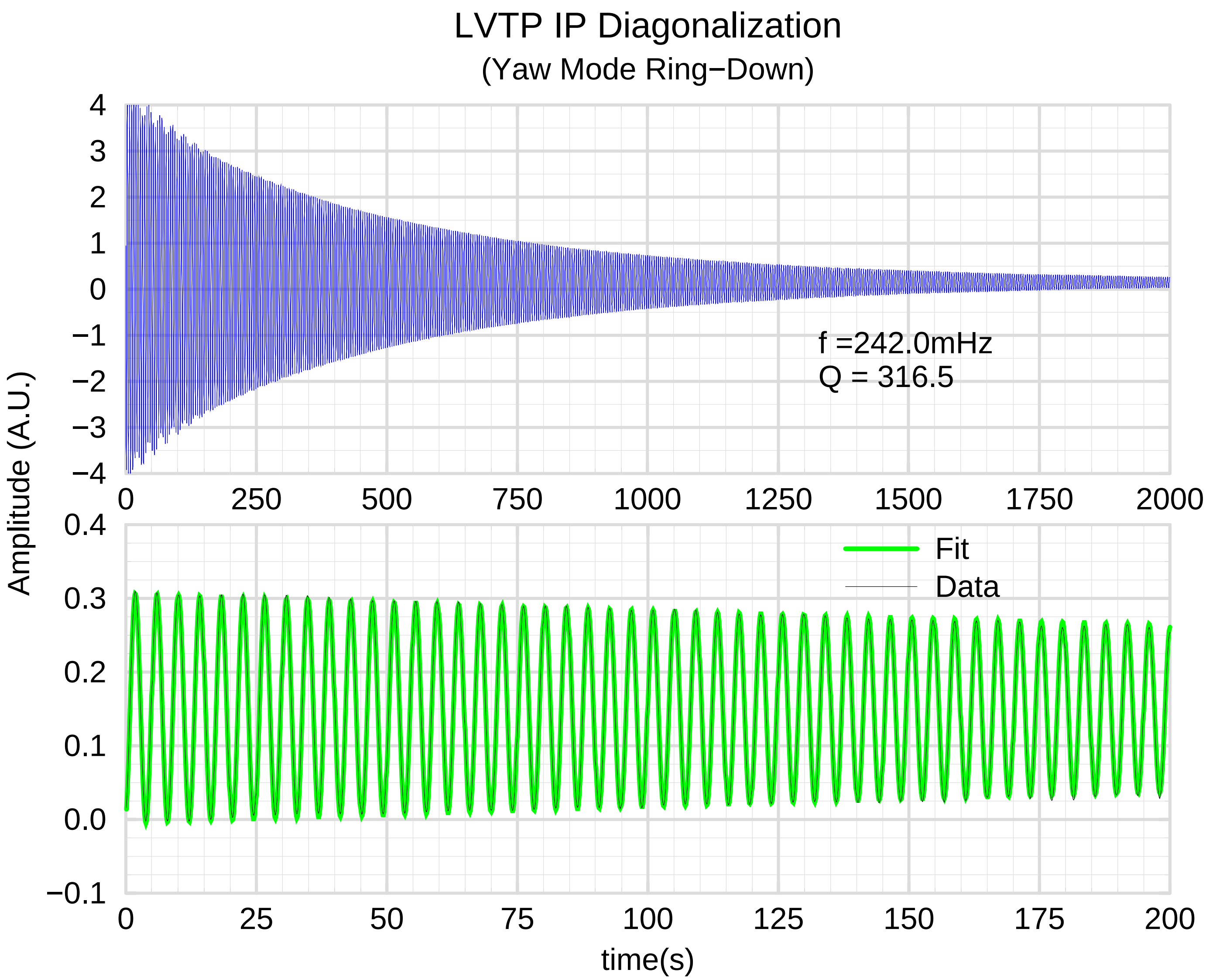


SAS-SUS LVDT

(Diagonalized Transfer Function Degenerate case)



Normal Mode RingDown (Yaw Mode)



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SAS Passive Attenuation Chain

- The Passive Attenuation Concept !
- Add pendulum stages to pile up $1/f^2$ attenuation factors until enough attenuation is reached.
- Done partly in SAS chain and partly in multiple pendulum suspensions
  - Note: the multiple pendulum main task is mainly to provide controls for the interferometer's locking and for thermal noise suppression
  - APS April 2000, Long Beach, Erika D'Ambrosio, "Characterization of a Low Frequency Power Spectral Density f^{-g} in a Threshold, Multi-stable Model"
  - APS April 2000, Long Beach, Eric Black "Thermal noise in coupled harmonic oscillators."
- Made of Modular and Simple Filters

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What is the difficulty in a Passive Attenuation Chain?

- To build a vertical oscillator at low enough frequency
  - So that it has a fundamental frequency easy to damp (<400 mHz)
  - So that its attenuation properties are on in the frequency ROI (>10 Hz)
- To avoid making creaking or creeping noises.
- The solution is GASF or MGASF
- APS April 2000, Long Beach, Akiteru Takamori, “Performance of Geometric Anti-Spring Filter (GASF) for Seismic Attenuation in Advanced Gravitational Wave Detectors”
- APS April 2000, Long Beach, Hareem Tariq, “Novel Design and Preliminary Testing of Linkless Geometric Anti Spring Filter Pre-Isolation”

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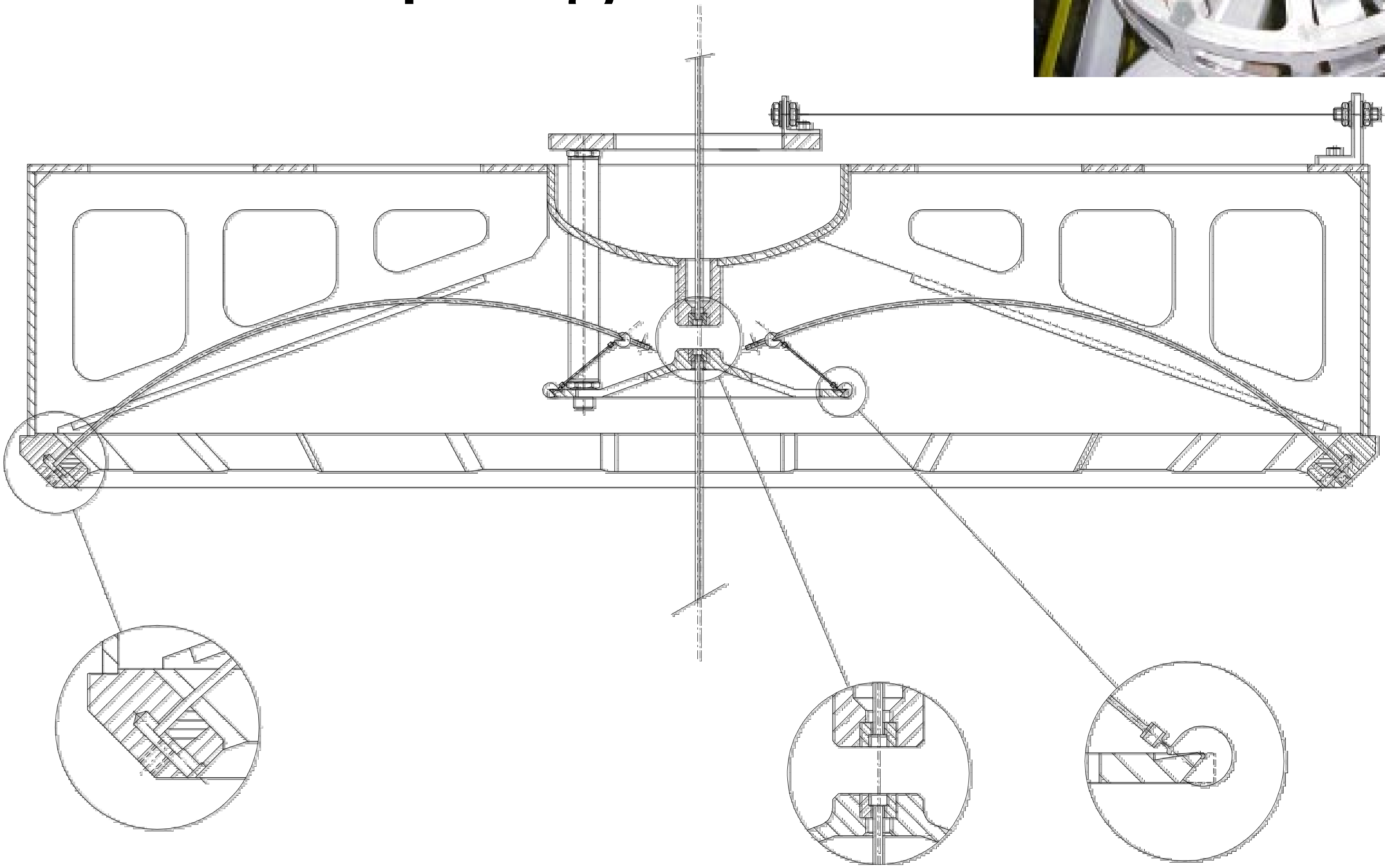
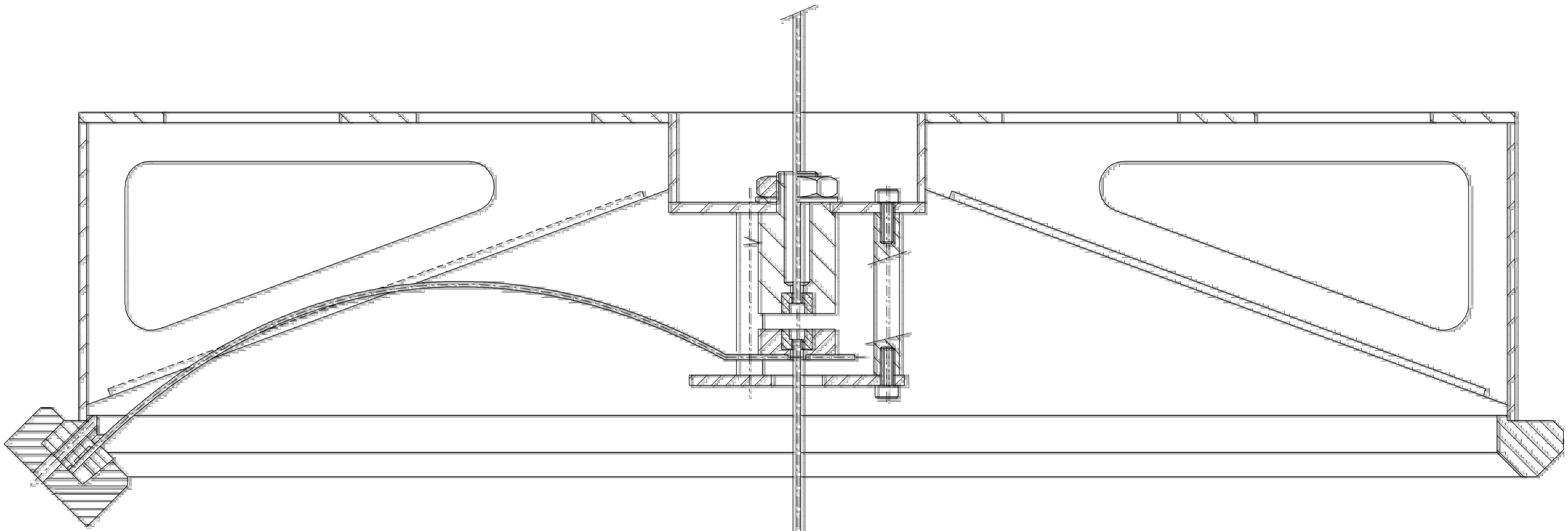
Geometric Anti Spring Filter



APS April 2000, Long Beach, Akiteru Takamori, “Performance of Geometric Anti-Spring Filter (GASF) for Seismic Attenuation in Advanced Gravitational Wave Detectors”



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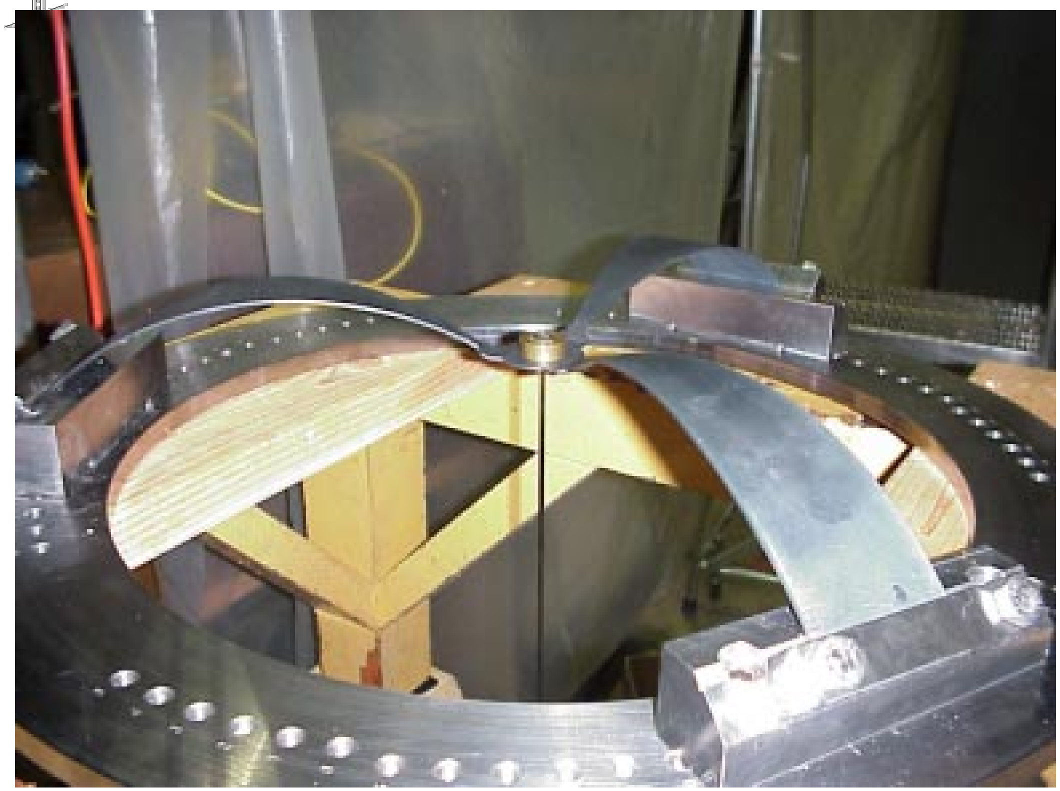
Monolithic GASF



APS April 2000, Long Beach, Hareem Tariq, “Novel Design and Preliminary Testing of Linkless Geometric Anti Spring Filter Pre-Isolation”

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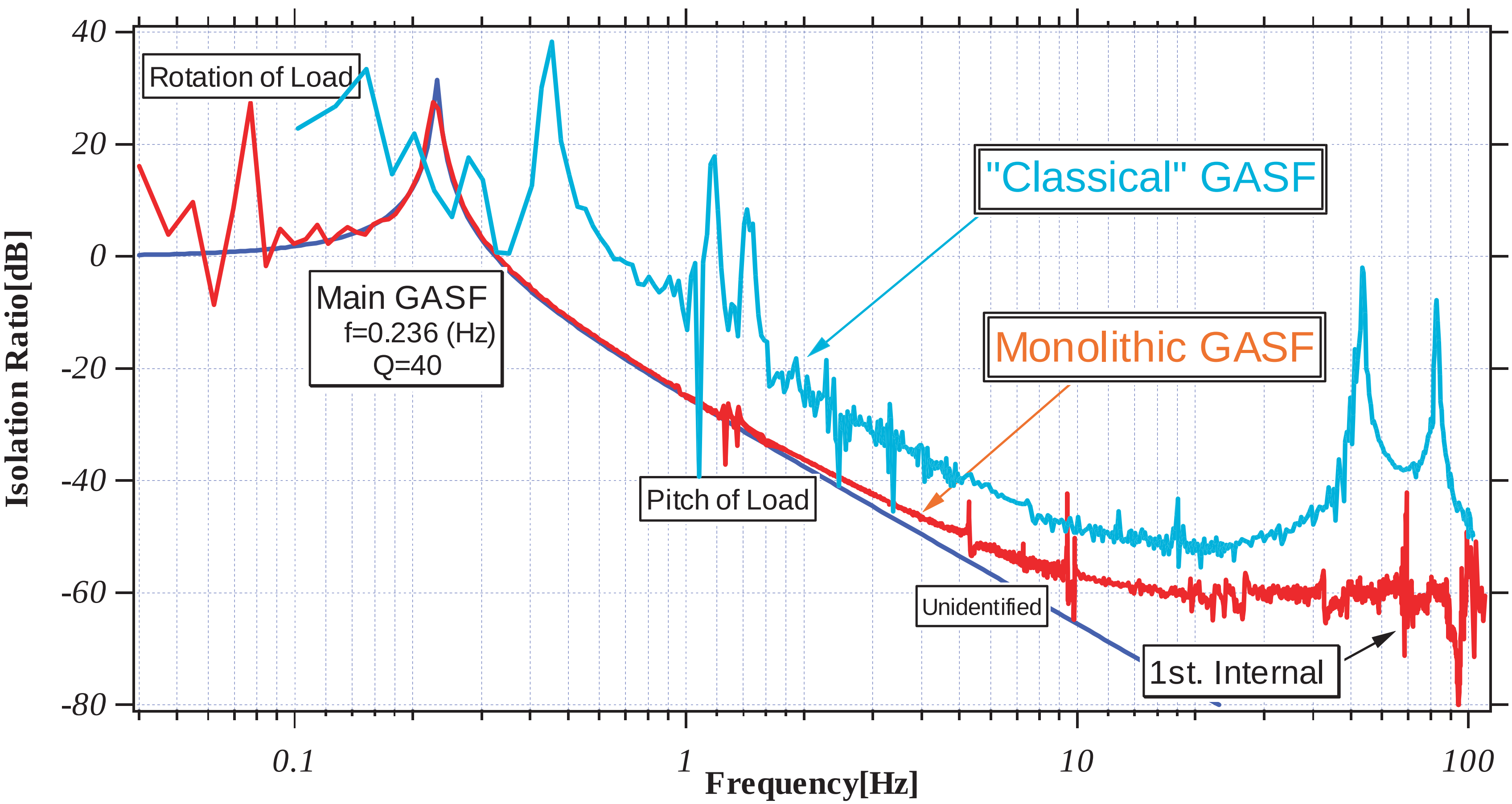
GASF / MGASF Performance



LIGO SAS

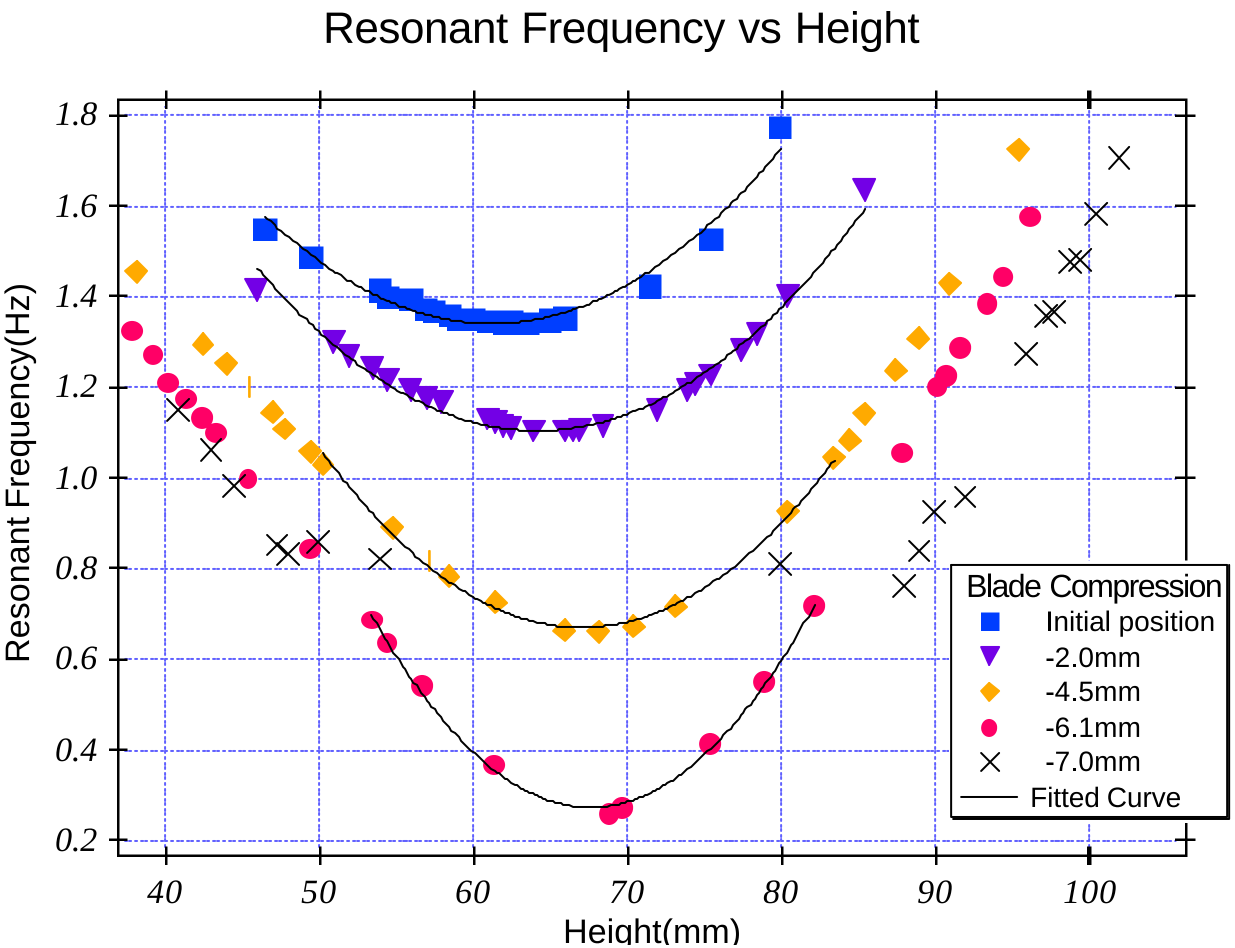
Tuning of Resonant Frequency

■Compression of the Blade

■Weight of the Load

- Resonant frequency

  Minimum ~220mHz



SAS Advantages of Passive Attenuation chains

- Simple Chain of modular pre-tested units
- It is passive, it always work,
- Losses of power, ineffectual,
- Irreversible drooping < 10^{-12} m/day
- No software => no bugs
- No actuators => no excess noise in frequency ROI
- More defensible when finding a signal

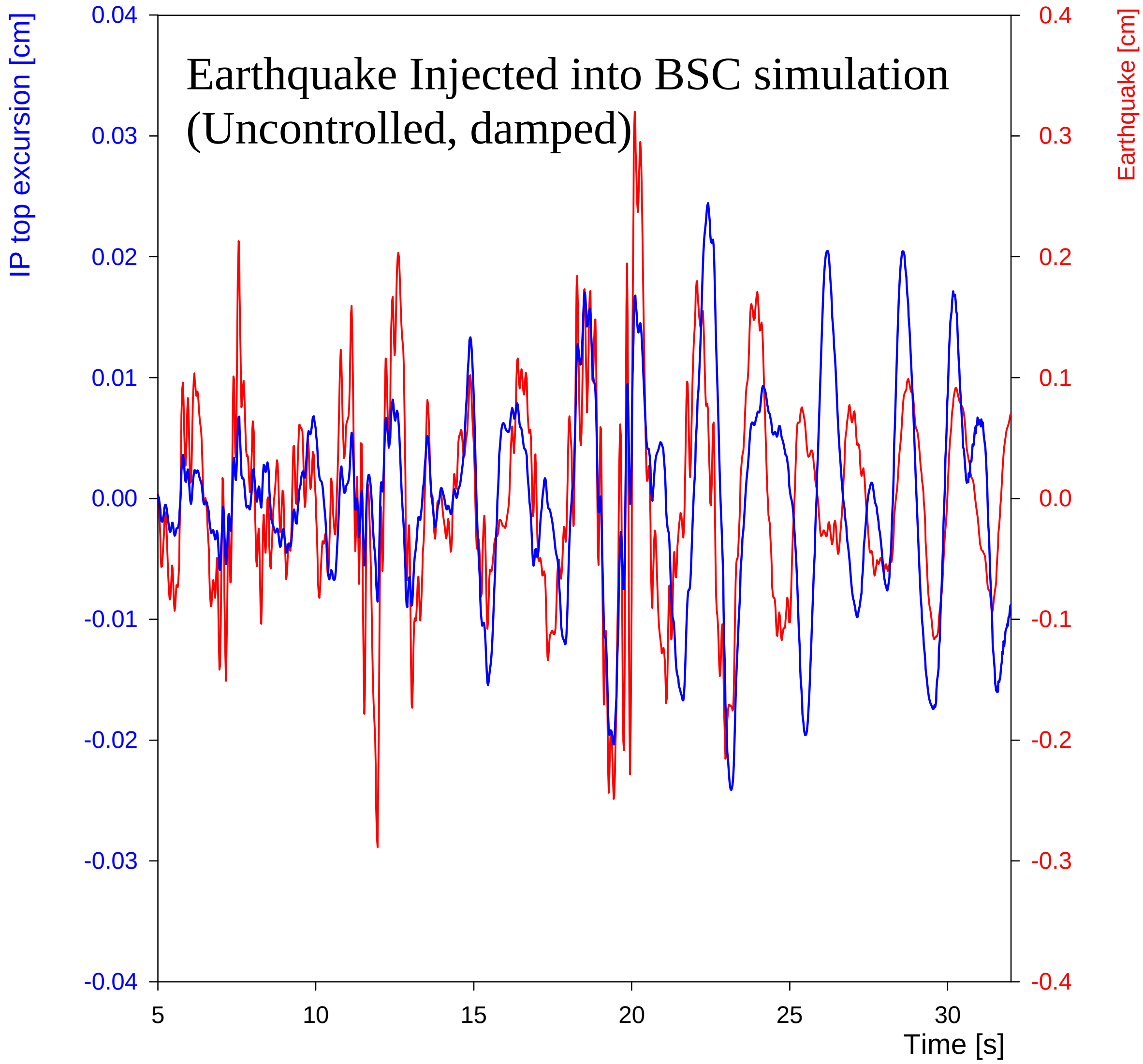
SAS Advantages of Passive Attenuation chains

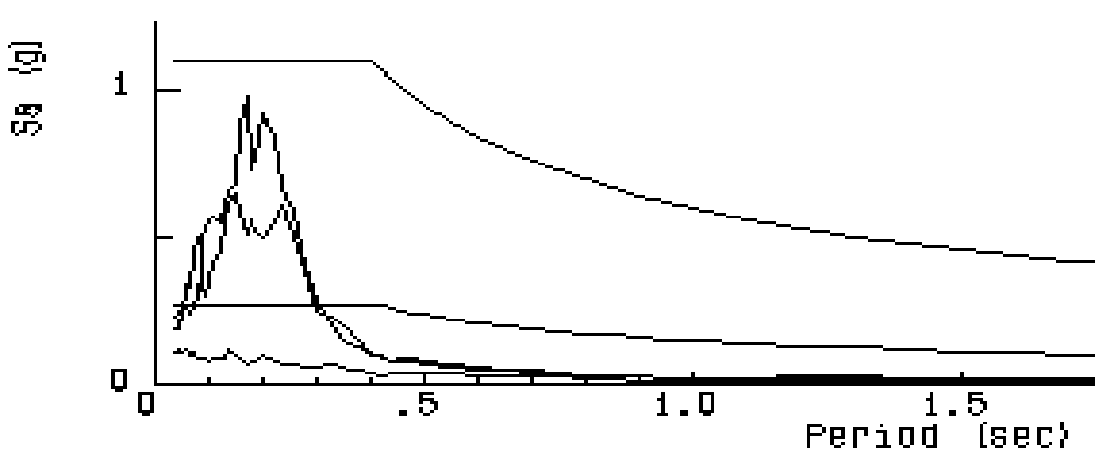
- A passive system means no active components in vacuum
  - (including the active inertial damping system)
- No need for encapsulated sensors
  - (no entrapped gases)
- Full Bakeability for ULF performance

LIGO SAS Expected Performances of Passive Attenuation chains

- Multiple pendulum suspensions positioning < 0.1 microns
- (1 micron achieved by Virgo, 0.01 micron calculated,
    - 0.1 micron aimed at)
        - ⇨ fully electrostatic plus photon drive
        - ⇨ possible in triple pendulum!!
        - ⇨ totally free test mass during interferometer running
- Large passive seismic attenuation overkill.
- APS April 2000, Long Beach, Giancarlo Cella, “MSE: a mechanical simulation engine for the LIGO end to end model”
- Not only more defensible, but also impervious to earthquakes
    - » earthquake performance figure

CAPE MENDOCINO EARTHQUAKE, 04/25/1992 11:06
40.026N, 124.069W, SHELTER COVE - AIRPORT





Expected Performances of Passive Attenuation chains

- Multiple pendulum suspensions positioning < 0.1 microns

- Large passive seismic attenuation overkill.

- APS April 2000, Long Beach, Giancarlo Cella, “MSE: a mechanical simulation engine for the LIGO end to end model”

- Not only more defensible, but also impervious to earthquakes

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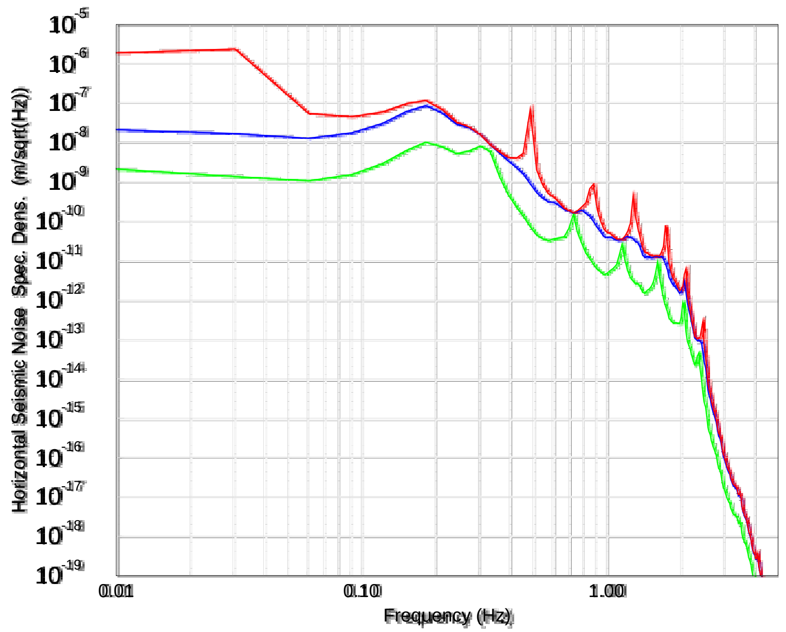
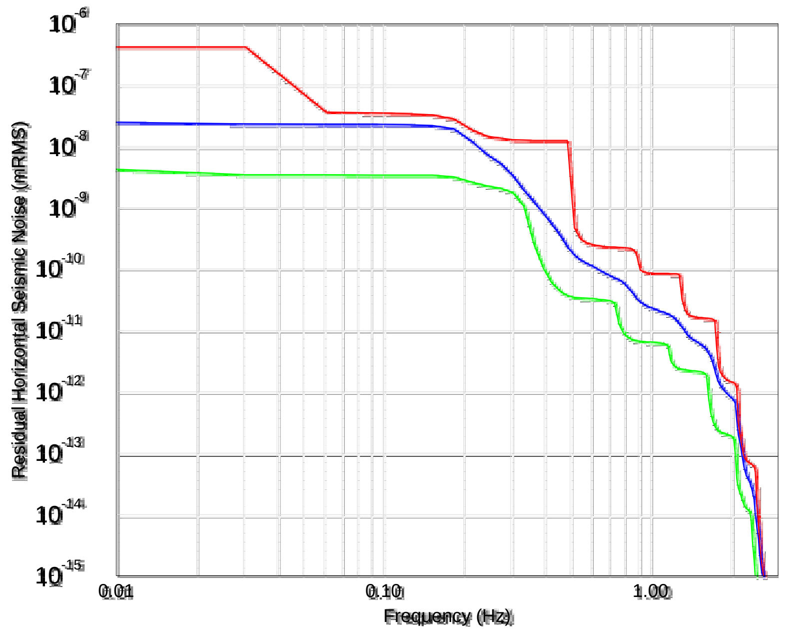
Simulated Attenuation Performance

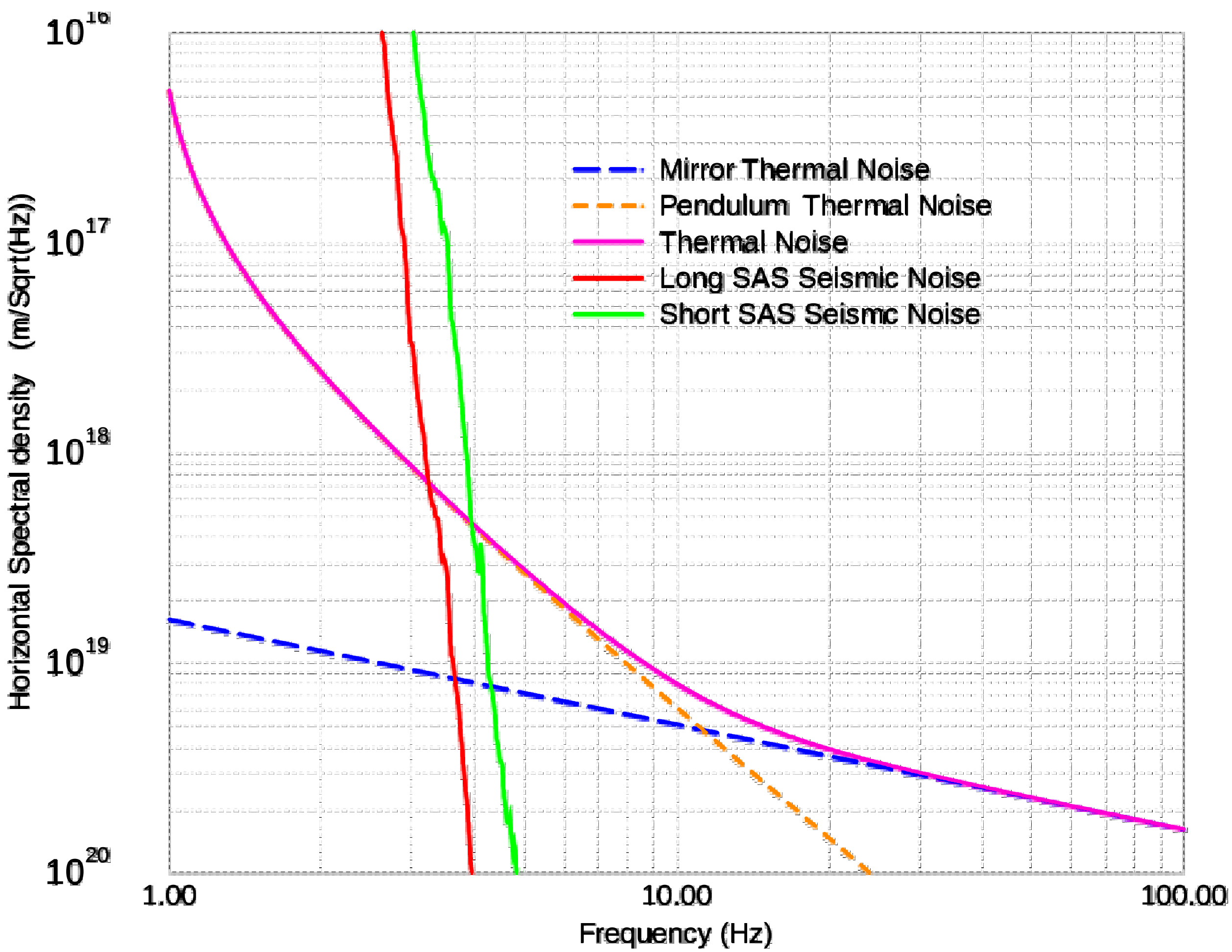


Simulated Residual Motion Performance



SAS

Attenuation Performance of a SAS chain



Wireless electrostatic mirror actuation

F. Nocera, A. Bertolini, R. DeSalvo, S. Marka

Why?

- kill a source of non-Gaussian noise

Force requirements:

- 1 mN to control 1 μm RMS residual motion

A possible solution:

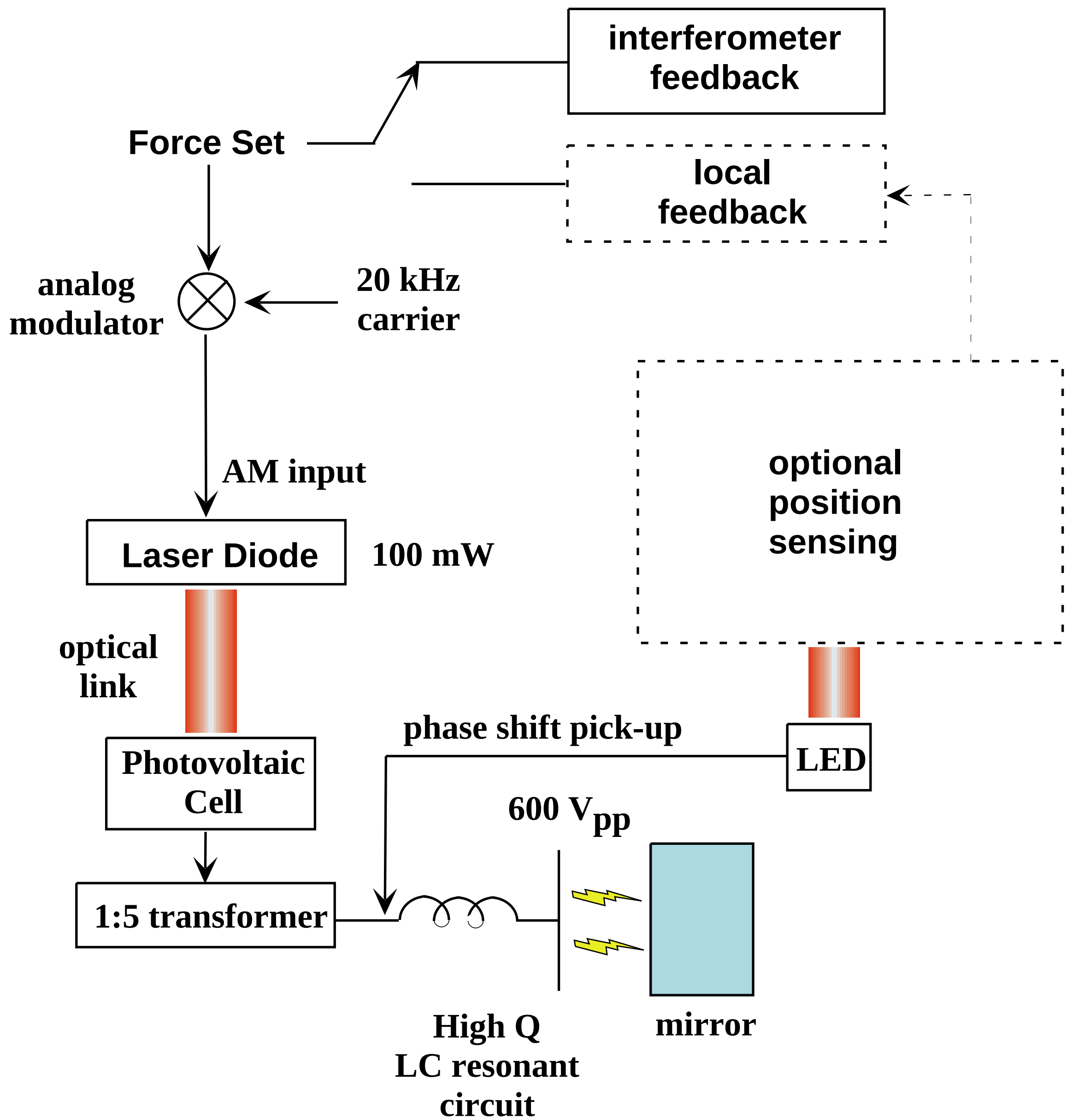
- optical transmission of power

- use strip array capacitors to increase capacitance and linearity

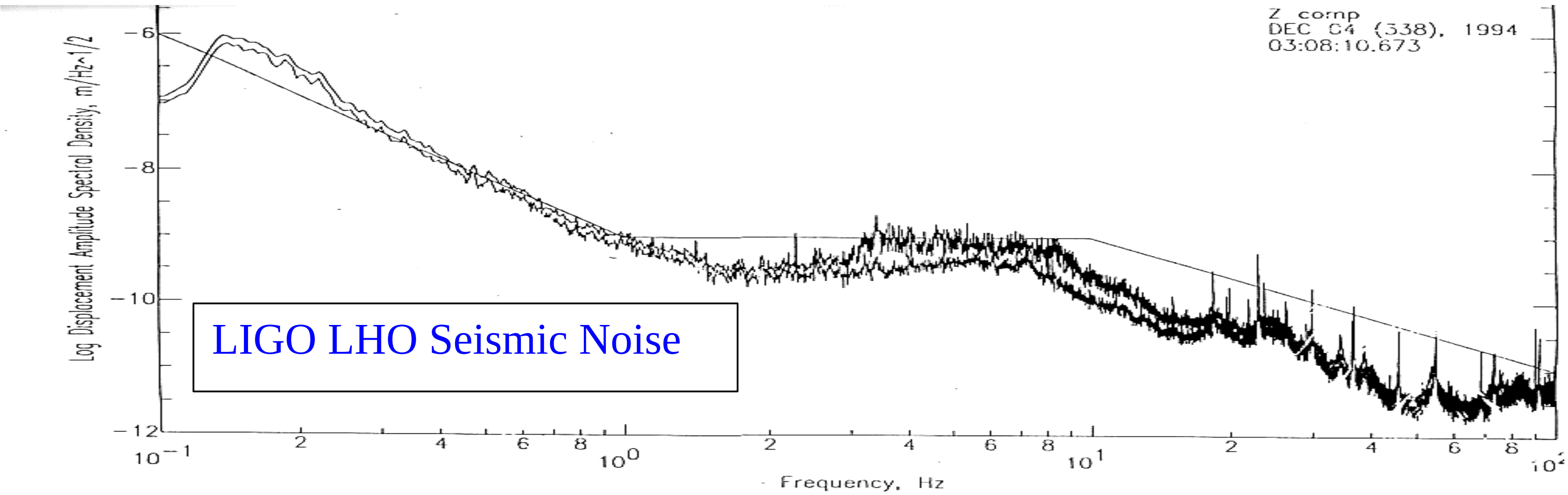
- drive the actuator with a high Q resonant circuit to have high voltage and low power consumption

Wireless electrostatic mirror actuation

Single capacitance driving scheme



LIGO LLO/LHO Seismic Noise Spectra on a quiet day



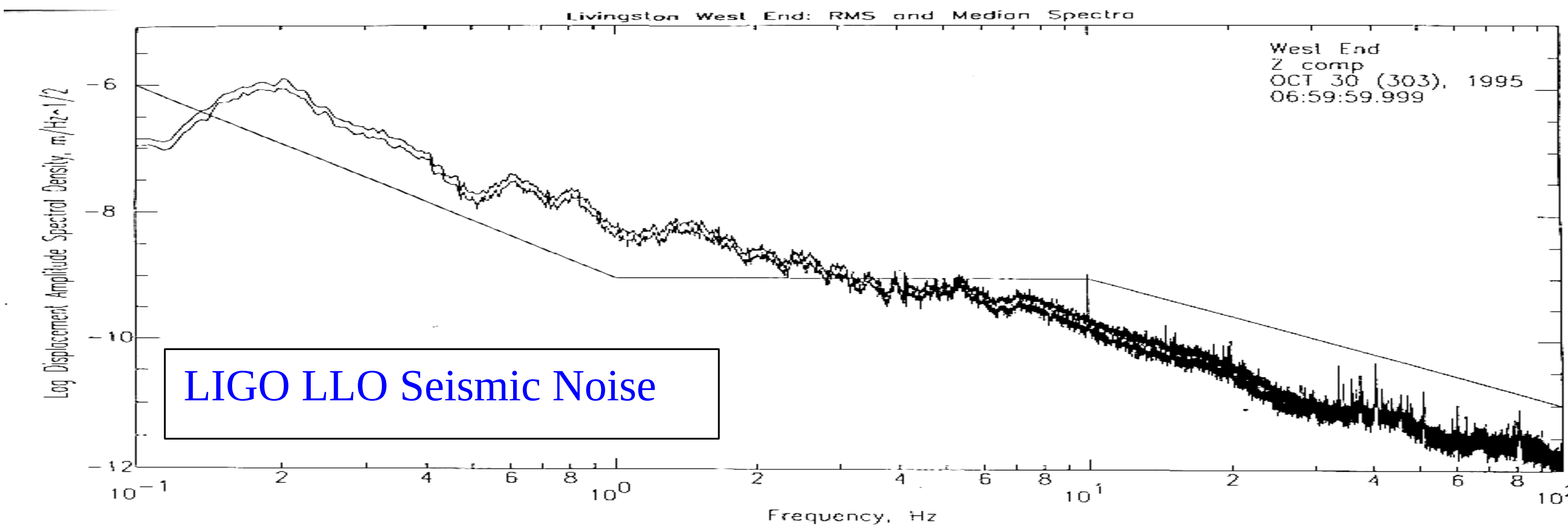


Figure 6-5. Amplitude spectra (median and r.m.s.) for a quiet one-hour period at the West End. This period corresponds to the same time period as the spectra shown in Figure 6-1. Vertical component is shown.